(4)

GL-TR-89-0155

MHD Modeling of Solar and Interplanetary Processes

Murray Dryer

NOAA/ERL
Space Environment Laboratory
Boulder, CO 80303-3328

April 1989

Final Report
1 October 1986-30 September 1988

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; Distribution unlimited.	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE			
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S) GL-TR-89-0155	
6a. NAME OF PERFORMING ORGANIZATION NOAA/ERL Space Environment Laboratory	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Geophysics Laboratory	
6c. ADDRESS (City, State, and ZIP Code) Boulder, CO 80303-3328		7b. ADDRESS (City, State, and ZIP Code) Hanscom AFB Massachusetts 01731-5000	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Project Order GLH7-6017 and GLH8-6004	
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS	

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
61102F	2311	G4	AA

11. TITLE (Include Security Classification)
MHD Modeling of Solar and Interplanetary Processes

12. PERSONAL AUTHOR(S)
Murray Dryer

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
FINAL	FROM 10/1/86 TO 9/30/88	1989 April	28

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	MHD modeling, Solar flare generated shock
03	01		Interplanetary medium, Geomagnetic storm
03	02		Solar-Terrestrial Physics,

19. ABSTRACT

Our objective has been to use magnetohydrodynamic ~~(MHD)~~ numerical modeling and simulations as tools to understand the physics of energy and momentum transport from the solar surface through the corona to interplanetary space. To achieve this goal, we have first identified possible physical mechanisms and, second, ~~have~~ performed synthesis calculations using self-consistent MHD theory via numerical and analytical methods. Solar and interplanetary (remote-sensing and *in situ*) observations play important roles in our synthesis strategy. ~~Our~~ models, unique in the field of solar/interplanetary physics, include both 2 1/2-D and 3-D time-dependent codes that, we believe, will lead to future operational status in geomagnetic storm forecasting procedures. ~~Our~~ strategy is oriented toward assuring that real-time observations would be used to drive physically based models, the outputs of which would be considered by space environment forecasters.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Don Smart	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL GL/PHP

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

Following a short Introduction, this ~~Final~~ Report consists of a Summary providing highlights of this research project. A Bibliography of papers, tabulated by first author for easy reference, follows the Summary. The various papers are categorized with a description of their main points and conclusions. A set of representative figures, with extensive descriptive captions, is included for the reader interested in additional details.

This work was prepared with partial support from several AFGL project orders to NOAA's Space Environment Laboratory during Fiscal Years 1987 and 1988. This support is acknowledged in each of the Bibliography's 28 papers that are now published, in press, or under consideration in scientific refereed journals and symposium proceedings.

INTRODUCTION

Our research strategy has focused on photosphere-corona-interplanetary coupling studies. Models within each domain were mathematically constructed on the assumption of physical mechanisms describable (generally) under the MHD paradigm. The mathematical constructs were then programmed for computer simulation; initial boundary value problems were studied using observations when available, and, whenever feasible, compared with spacecraft or ground-based observations. Linkages between the domains were attempted in some cases; that is, the output from one model provided input for another model in the next domain.

Some examples that illustrate this strategy are shown in an overview presentation in Figure 1, prepared in collaboration with Prof. S. T. Wu of the Center for Space Plasma and Aeronomic Research at the University of Alabama in Huntsville. The *upper left* panel shows, in sub-panel (a), photospheric vector magnetograph observations provided by the Air Weather Service's Solar Optical Operational Network (SOON) and the NASA/Marshall Space Flight Center. A nonlinear, force-free model was then used, with the observed photospheric data from sub-panel (a), to extrapolate the magnetic topology into the corona as shown in sub-panel (b).

The *lower left* panel of Figure 1 illustrates the use of the extrapolated closed magnetic field lines in a study of non-equilibrium that may be caused by relative shear motion [sub-panel (a)] of the photospheric footpoints. This loss of equilibrium may be one of the causes of coronal mass ejections (CMEs) as shown in sub-panel (b). It was found that the arcade in sub-panel (a) becomes unstable and is ejected to the lower corona when the relative shearing velocity reaches a critical value.

These results were then extended as inputs to the corona, where we investigated the response as shown in the *upper right* panel of Figure 1. Sub-panel (a) shows the initial 20-minute-duration input of mass injection at the location of a dipole magnetic field configuration as shown in sub-panel (b). The density at that location was increased by a factor of five, and the temperature was reduced by this same factor in order to maintain a constant coronal base pressure. Sub-panel (c) shows the simulated density increase 5,500 seconds after the initiation of the mass injection. The outward propagation of an MHD fast mode shock wave is shown with an extensive region of retarded, compressed mass and the confinement of two MHD, slow-mode shock waves within the dynamically confined, low-beta plasma in the inner, closed, magnetic-loop region.

Finally, we studied the interplanetary response to some specific solar events as shown in the *lower right* panel of Figure 1. Sub-panel (a) shows a radio astronomical interplanetary scintillation (IPS) observation of the disturbed solar wind density in September 1980, just after a solar flare near the maximum of Cycle 21. Sub-panel (b) shows the results of our three-dimensional, time-dependent, MHD simulation of density compression and rarefaction regions for this event. The resemblance (to be discussed later in this report) between the IPS observation and our simulation is noted, indicating that our physical model is valid. Sub-panel (c) shows our 2 1/2-D MHD simulation of the solar wind density response in the ecliptic plane during a series of major solar flares and CMEs in February 1986 near the *minimum* of Cycle 21. Spacecraft data at the indicated locations (Earth, GIOTTO, and SAKIGAKE) were used for comparison with our simulation.

The above studies were performed separately at three locations: the lower solar atmosphere (photosphere), the mid-solar atmosphere (corona), and the "upper" solar atmosphere (interplanetary space). Figure 1's objective is merely to show that such a coupled study is possible. Clearly, a number of assumptions have been made and are subject to review. This kind of MHD modeling study should be continued in order to make significant progress in the understanding of physical mechanisms for energy and momentum transport through the solar-interplanetary environment.

Our methodology in pursuit of this strategy is given in the Summary below. A short description of key points and conclusions is given in each of four categories:

A. Basic solar wind studies.

B. Magnetohydrodynamic, time-dependent, 2 1/2-D and 3-D models for the solar wind plasma and interplanetary magnetic field (short title: MHD Modeling).

C. Coronal mass ejection studies.

D. Technology transfer for geomagnetic storm prediction studies (short title: Technology Transfer).

The Summary will be followed by a Concluding Remark, the Bibliography, and eight Figures discussed in the Summary.

SUMMARY

A. Basic Solar Wind Studies

The objective of this work is to probe deeper into the fundamental plasma properties that underlie the collective nature of the solar wind plasma, its multi-fluid nature, its transport properties, and its relation to the interplanetary magnetic field (IMF). The strategy followed in this work is carried out by the rigorous use of higher moment equations, particle simulation computer codes, and solution of multi-fluid equations. We have included the following papers in this category:

Cuperman, Ofman, and Dryer (1986)
Cuperman, Yatom, Dryer, and Lewis (1987)
Cuperman, Ofman, and Dryer (1988)
Cuperman, Detman, and Dryer (1988)
Cuperman, Ofman, and Dryer (1989)

In the first paper, Cuperman, Ofman and Dryer (1986) utilized particle simulation experiments to investigate the nonlinear behavior of plasmas with a mixture of anisotropic protons, electrons, and isotropic alpha particles embedded in a static magnetic field. The physical processes involved in the collisionless interaction of the mixed protons and heavier alphas are discussed. In particular, the interaction with initially cold alphas causes heating of the alphas by non-resonant interaction with proton-produced, ion-cyclotron electromagnetic waves. Initially warm alphas, in contrast, are heated by resonant interaction with these waves. This work is relevant to the eventual description of a three-fluid solar wind within the MHD modeling context.

Cuperman, Yatom, Dryer, and Lewis (1987), in another fundamental paper, generalized results from a previous paper in which were analytically derived the most probable velocity distribution function of each component of a non-equilibrium, multispecies, spherically symmetric system of particles for the case in which the component was described by the first *seven* moments of the distribution function. These moments are: particle density; radial streaming velocity; random radial kinetic energy; random transverse kinetic energy; radial transport of random radial kinetic energy; radial transport of random transverse kinetic energy; and a moment that reflects the non-Maxwellian features of the core, intermediate range, and tail particles. It was found that there is no limitation on the thermal anisotropy in the theory that extends each species in terms of the first *nine* moments (including different components of the heat flux and of the fifth moment) of each distribution function. This nine-moment description was used to compute a wide range of non-maxwellian proton distribution functions that have been observed in the solar wind.

The nonlinear behavior of mixed proton-alpha plasma systems was investigated again via the particle simulation approach (Cuperman, Ofman, and Dryer, 1988). Waves generated by anisotropic proton populations produced a strong damping of parallel-propagating electromagnetic ion-cyclotron waves and a dip in the energy spectrum, both centered at the alpha cyclotron frequency.

Our objective for developing multi-fluid solar wind models was advanced by Cuperman, Detman, and Dryer (1988), who derived a two-fluid, steady-state solution in which the electron and proton thermal conductivities are coupled. This important advance represents changes in the direction required to improve the matching of theoretical predictions and observations at 1 AU. That is, they reflect a redistribution, as shown in Figure 2, of the total energy flux among the various types of energy in the quiet solar wind, namely, kinetic, thermal, conduction, and gravitational. These results, however, do not eliminate the necessity for including additional, noncollisional, physical processes operating in the solar wind.

An improvement to existing helmet-streamer (coronal structure) solar wind MHD models has recently been made by Cuperman, Ofman, and Dryer (1989). Unlike previous isothermal models, this new model incorporates thermal conduction and continuous subsonic-supersonic solutions that observe boundary conditions at the Sun as well as the vanishing of the temperature at infinity. This axisymmetric solution incorporates an explicit solution of a flat heliospheric current sheet as well as the procedure for its extension to three dimensions.

Our intent, of course, is to fold results and ideas from these fundamental studies into the major thrust of our research, MHD modeling of solar and interplanetary processes. The interplanetary aspect of this work is summarized in the following section.

B. MHD Modeling

The objective of this work is to develop computer simulation models that describe the zeroth-order response of the heliospheric plasma and interplanetary magnetic field (IMF) to various forms of solar activity. The strategy pursued in this work is the development of multi-dimensional MHD computer codes that input solar parameters provided by observational diagnostics of flares, coronal holes, and erupting prominences. The output is then compared whenever possible with *in situ* spacecraft data as well as by remote-sensing interplanetary scintillation (IPS) techniques. We have included the following papers in this category:

Chao, Wu, Wu, and Dryer (1988)
Dryer and Smith (1986)
Dryer, Smith, and Wu (1988)
Dryer, Detman, Wu, and Han (1989)
Garcia and Dryer (1987)
Han, Wu, and Dryer (1988)
Han, Wu, and Dryer (1989a)
Han, Wu, and Dryer (1989b)
Panitchob, Wu, and Dryer (1986)
Smith, Yeh, Dryer, Watanabe, Hirosawa, Yamamoto, and Oyama (1989)
Tappin, Dryer, Han, and Wu (1988)
Tappin, Dryer, Han, and Wu (1989)
Wu, Dryer, and Han (1987)
Wu, Dryer, and Han (1988)

The first paper, Chao, Wu, Wu, and Dryer (1988), is limited to a one-dimensional, time-dependent study of slow MHD shock evolution in the solar wind. Using a Cartesian coordinate system with all three velocity and magnetic field components, a slow shock that propagates into a positive density gradient is observed to evolve into an intermediate shock. In a second calculation with spherical coordinates and an Archimedean IMF, the slow shock retained its identify, with a fast reverse shock forming behind it and a fast rarefaction wave forming ahead of it.

The 2 1/2-D Interplanetary Global Model (IGM) was used by Dryer and Smith (1986) to simulate the multiple interplanetary disturbances during the STIP Interval VII in August 1979, near the maximum of Solar Cycle 21. Figure 3 shows the comparison of simulated velocity and IMF magnitude with the observed data. The IMF comparison is more satisfactory than that for the velocity, despite some phasing discrepancies that illustrate our incomplete knowledge of the various forms of solar activity and ability to mimic their forms of energy and momentum input to a real, 3-D heliospheric flow.

In an invited review paper for a special journal issue dedicated to Professor Hannes Alfvén 's 80th birthday, Dryer, Smith, and Wu (1988) provided representative examples of solar and interplanetary physics from the macroscopic point of view. They noted that the continuum approach to global problems, keeping in mind the assumptions and limitations therein, can be very successful in providing insight to and large-scale interpretations of otherwise intractable problems in space physics.

Dryer, Detman, Wu, and Han (1989) have recently used the 3-D IGM to study the propagation of plasmoids through the solar wind. They studied two separate cases: (1) solar-ejected, diamagnetic plasmoids that retain their closed (albeit expanding) topology to and beyond Earth; and (2) plasmoids that are formed, in the corona near the Sun or in the solar wind, as a consequence of post-shock-induced reconnection of opposite-directed IMF lines at the heliospheric current sheet.

A 3-D demonstration of the IMF deformation around the plasmoid in Case (1) above is shown in Figure 4. In this case, an initially spherical plasmoid with a "slinky-like" magnetic topology was injected at 18 solar radii (in the 3-D IGM) with a velocity twice that of the background solar wind velocity (250 km/s) at that location. One set of plasmoid magnetic field lines, shown after 72.6 hours, is seen to be strongly elongated in the fields projected onto the lower side of the 3-D, 1 AU-sized box. Most of the IMF lines are deformed by the leading fast-mode MHD shock and are draped around the plasmoid. Several IMF lines, however, come into close proximity with the plasmoid and, as a result of "numerical" reconnection, are wrapped around the inside of the plasmoid before returning to the external solar wind. These "close-in" IMF lines exhibit substantial polarity changes out of the ecliptic plane. These cases of polarity change have implications of geomagnetic substorm initiation (southward turning of the IMF) or termination (northward turning).

Another specific event that had very significant solar, interplanetary, and geomagnetic consequences in February 1986 (at the minimum of Solar Cycle 21) was examined by Garcia and Dryer (1987). These workers used the GOES full-disk, soft x-ray data and the SOON/RSTN observations to provide input parameters for the 2 1/2-D IGM. Part of the results of this study is shown in Figure 5. The authors were able to simulate very accurately the arrival of the shock from one of the flares ("Flare 5") at Earth where an SSC occurred with a major geomagnetic storm. They were, however, unable to obtain a satisfactory post-shock velocity profile. More recent studies (Coates, Johnstone, Dryer, and Smith, in preparation, 1989) indicate that a satisfactory velocity profile at IMP–8, at Earth, and at GIOTTO (see Figure 1, lower right panel) could be simulated for an assumed long-lasting energy outflow (for ~ 24 hours) from Flare 5 (6 February 1986, 0625 UT; 3B/X1.7).

The 3-D IGM is described in extensive detail (basic one-fluid, MHD, infinitely conducting equations; numerical algorithm and methodology, etc.) by Han, Wu, and Dryer (1988).

The numerical methods for both the steady-state and the transient models are a variant of the Lax-Wendroff finite-difference scheme. Our specific time-dependent, 3-D application is new to the field of interplanetary physics. Han, Wu, and Dryer (1989a) have presented much of the same information as well as an extended set of graphical presentations that, for a complex 3-D problem of this magnitude, are essential for conveyance of physical and interpretive concepts. We have also experimented (Han, Wu, and Dryer, 1989b) with a thermally conductive, one-dimensional, numerical study of transient flows that start at one solar radius rather than 18 solar radii as in the case of the 2 1/2-D or 3-D IGMs.

The February 1986 events described above were also examined by Smith et al. (1988) from another point of view, namely a comparison of Doppler scintillations with a parameter $nV_{\perp}$ derived from the 2 1/2-D IGM. The daily Doppler scintillation measurements were made by the tracking data to SAKIGAKE; these scintillations are believed to be due to the temporal and spatial changes in the mass flux in the region traversed by these signals. This mass flux is given by $nV_{\perp}$ where n is the solar wind density and $V_{\perp}$ is the solar wind velocity component transverse to the line of sight from Earth to SAKIGAKE (Figure 1, lower right panel).

Comparison of the MHD line-of-sight integration and the interplanetary scintillation Doppler signal (IPDS), as shown in Figure 6, is encouraging. This particular numerical experiment with the 2 1/2-D IGM demonstrates the utility of using a line-of-sight telemetry signal, the *in situ* observations (Garcia and Dryer, 1987; Coates et al., in preparation, 1989), and the MHD model for meaningful comparisons. Another technique is described below.

The interplanetary scintillation (IPS) technique is the only remote-sensing system that can provide synoptic "snapshots" of global interplanetary solar wind compressions and rarefactions. A large radio telescope (30,000 m^2 in England and 20,000 m^2 in India) has the sensitivity to measure, at 81.5 and 103 MHz, respectively, the signals from more than 1000 distant radio galaxies. The r.m.s. scintillating flux of these signals is normalized to the mean scintillating flux from the same radio sources at the same solar elongation (Sun-Earth-source angle) when averaged over a year's data base. This ratio has been shown to be proportional to the solar wind density fluctuations and, in fact, to the density itself. Hence maps of solar wind compressions and rarefactions, as seen in Figure 1 (lower right panel), have been made on a daily basis from 1978–1980 at Cambridge, England. We have utilized the 3-D IGM to generate simulated maps of this kind with an assumption that the driving function is a solar flare- or eruptive-prominence-generated interplanetary shock wave as shown by Tappin, Dryer, Han, and Wu (1988, 1989). The example shown in Figure 1 (lower right panel) is repeated in Figure 7 in order to illustrate some of the details, as discussed below.

To summarize this recent development of IPS remote-sensing capability and the applicability of the 3-D IGM for interpretive purposes, it has been demonstrated that it is now possible to image the interplanetary medium from elongations of about 35 degrees to beyond the orbit of Earth. Interplanetary scintillation indices, computed on the basis of density-controlled turbulence along the line of sight from an array of radio galaxies to the ground-based antenna at Cambridge University in England, have been used to track solar-generated disturbances (from flares, coronal holes, and erupting prominences) on this globally significant scale.

The example shown in Figure 7 compares, for interpretive purposes, a 3-D MHD model for the interplanetary propagation of a flare-generated shock wave that showed the appropriate compression and rarefaction to be in reasonably good agreement with the observations. In the latter model, an integration was made along the line of sight through the temporal and spatial density structure of the disturbed solar wind. Note that the circle is that viewed by the Earth-bound observer as he or she "moves" along the dawn-dusk meridian and looks toward the local zenith.

Efforts are currently underway in England (to re-activate the Cambridge antennae) and in India (to double the size of the largest—presently 10,000 square meters—of the three antennae near Ahmedabad's Physical Research Laboratory) to upgrade this demonstration of interplanetary imaging capability. The Principal Investigator of this Final Report is the U.S.' Principal Investigator on the Indo-U.S. project and is also affiliated with the U.K.-U.S. project. When data from these projects become available to SEL, efforts will be made to share them with AWS.

Finally, Wu, Dryer, and Han (1987, 1988) summarized (for the computational fluid dynamics community) some of the applications of the 3-D IGM to interplanetary shock and plasmoid problems. They also noted the use of 2-D models for CME simulations.

C. Coronal Mass Ejections (CMEs)

The objective of this work is to examine more closely the solar activity as close as possible to the source of perturbations that emanate from the Sun and propagate into the interplanetary medium. The strategy pursued in this work is to perform theoretical analyses of mass ejections and erupting prominences (that may be detected as "magnetic clouds" in the solar wind) and numerical MHD studies of CMEs. We have included the following papers in this category:

Song, Wu, and Dryer (1987)
Song, Wu, and Dryer (1989)
Yeh (1987)
Yeh (1989)
Wu, Dryer, Steinolfson, and Tandberg-Hanssen (1988)

We have been concerned by a controversy surrounding the physical explanation for the initiation of CMEs. Having played a central role (from the MHD modeling point of view) in these studies since the initial observations of CMEs by OSO-8, Skylab, P78-1, and, now, SMM, we thought it appropriate to make an exploratory theoretical stability study of ejected cylindrical plasma columns (Song, Wu, and Dryer, 1987). With the use of linear MHD stability theory, we asked: why are some solar ejecta stable, and why do others disintegrate?

It was found that the initial plasma flow velocity has a significant effect on the instability criteria and growth rate. That is, the wave number range where instability may occur becomes wider with plasma flow; with increasing velocity the region of instability shifts to the short-wavelength region. Thus plasma columns, injected at high velocity into the corona, may break into small pieces resembling the so-called "melon seed" phenomena.

Complementary to current suggestions that CMEs may be triggered by loss of equilibrium of large-scale coronal magnetic field structures, we continue to believe that energy conversion, triggered by reconnection (as in a flare), should continue to be considered as a viable option for an important secondary (and even primary) source of CME generation. Thus we embarked on a fundamental study of soliton and strong Langmuir turbulence in solar flare reconnection processes (Song, Wu, and Dryer, 1989). We found that this turbulence can be identified with a sudden eruption of an electric current leading to a local vacuum in which an electric potential is formed with an associated release of a huge amount of free energy. This energy conversion process was illustrated with a numerical example in which the resistivity increased by 4–5 orders of magnitude above the classical value.

We also performed a basic study of polarity-neutral lines on the solar surface and the implication for the topology of magnetic structures that may be associated with CMEs (Yeh, 1987). It was found that there are fewer heliospheric current sheets (as revealed by magnetic neutral lines on the source surface) in interplanetary space than might be expected by the polarity-neutral lines on the solar surface. This is because there are two topologically distinct types of magnetic cells of closed field lines: closed and open. Only the open cells are overlain by current sheets. Yeh (1989) has also considered the dynamics of magnetic flux ropes that have been hypothesized for some CME structures. These flux ropes have also been suggested by others as the "magnetic clouds" that have been observed in the solar wind.

Responding to concern that some early CME simulations violated the solenoidality condition ($\nabla \cdot B = 0$) for an "open" magnetic topology, Wu, Dryer, Steinolfson, and Tandberg-Hanssen (1988) examined the effect of this violation. Using an improved code, they examined the effect on the physical validity of the numerical simulation (for a representative pulse input) for the case when solenoidality is deliberately violated as compared to the case when it is preserved. They found that the error in the energy density and in the plasma density profiles is rather small and, hence, does not violate our earlier conclusions about mass and wave motion.

D. Technology Transfer for Geomagnetic Storm Prediction

The objective of this work is to convert the research noted above into operationally useful algorithms that can easily and effectively be incorporated into tools for utilization by NOAA and USAF agencies. The strategy pursued in this technology transfer is to develop operational algorithms based on deterministic principles of solar cause and geophysical effects as revealed by the models discussed above. The strategy, then, is similar to that used in large-scale tropospheric weather forecasting but, in this case, it is for *space* weather forecasting. We have included the following papers in this category:

Dryer, Smith, Detman, and Yeh (1986)
Dryer, Smith, Wu, Han, and Yeh (1986)
Pinter and Dryer (1985)
Smart, Shea, Dryer, Quintana, Gentile, and Bathhurst (1987)

The AFGL Technical Report by Dryer, Smith, Detman, and Yeh (1986) was our first study of the February 1986 solar and geomagnetic events discussed above (Garcia and Dryer, 1987; Smith et al., 1989). Plots of various simulated interplanetary parameters are given in 5-hour intervals to assist in the interpretation of the colliding shocks from the various solar flares.

A review of our initial 2 1/2-D and 3-D IGM capabilities was presented to a magnetospheric audience by Dryer et al. (1986). The August 1979 period of STIP Interval VII, discussed above, was cited as an example of a complex series of events. A simple corotating stream was discussed as an example of a simple event. The Poynting flux at Earth, as well as the cross-tail electric field profile, was given as a proposed predictive capability of the 2 1/2-D IGM. The necessity of moving on to fully 3-D IGM, however, was stressed as was the need to evaluate the global effects of asymmetrical inputs at the Sun.

It has been proposed by Pinter and Dryer (1985; publication delayed by the first author's death) that the Shock-Time-Of-Arrival (STOA) operational model might be improved by using the duration of Type IV radio emission (rather than the GOES soft x-ray duration) as a phenomenological symptom of the piston-driven phase of a sample of 39 shocks from flares in 1972–1989. Figure 8 shows an "average," representative, shock velocity as a function of heliocentric distance as found from this study of large flares during this period. This work was inspired by the work of Smart et al. (1986) and the earlier work that established the basis of the STOA model that is presently validated and in use at USAF/GWC and NOAA/AWS at Offutt Air Force Base, Nebraska, and at SEL in Boulder, Colorado, respectively.

CONCLUDING REMARK

Our objective in this research has been to use MHD numerical modeling and simulations as tools to understand the physics of energy and momentum transfer from the Sun to outer space. In particular, we have focused attention on the *physical* modeling of propagating features toward Earth. Thus, we have avoided purely kinematic or phenomenological methods. We believe that our objective, to strive toward space weather codes (analogous to the global circulation models in terrestrial use), will be best served by this strategy. By its very nature, the problem is rapidly moving toward fully 3-D IGMs, an area in which we have pioneered with the support of NOAA/SEL, NASA, and USAF/AFGL, to whom we express our appreciation.

BIBLIOGRAPHY

Chao, J. -K., S. T. Wu, C. C. Wu, and M. Dryer, Evolution of Slow Shocks in the Solar Wind, in *Proceedings of Solar Wind Six*, (V. J. Pizzo, Ed.), Estes Park, CO, 24–28 August 1987, NCAR Report TN–306, pp. 441–445, 1988.

Cuperman, S., T. Detman, and M. Dryer, Effect of Coupled Electron-Proton Thermal Conductivities on the Two-Fluid Solutions for the Quiet Solar Wind, *Astrophys. J.*, **330**. 466–473, 1988.

Cuperman, S., L. Ofman, and M. Dryer, Nonlinear Aspects of Collective Electromagnetic Interactions in Mixed Anisotropic Proton-Isotropic Alpha Particle Magnetized Plasmas, *J. Plasma Physics*, **36**, 387–405, 1986.

Cuperman, S., L. Ofman, and M. Dryer, On the Dispersion of Ion Cyclotron Waves in H^+—H^{++} Solar Wind-like Magnetized Plasmas, *J. Geophys. Res.*, **93**, 2533–2538, 1988.

Cuperman, S., L. Ofman, and M. Dryer, Thermally Conductive MHD Flows in Helmet-Streamer Coronal Structures, *Astrophys. J.*, submitted, 1989.

Cuperman, S., H. Yatom, M. Dryer, and D. Lewis, Theoretical Non-Maxwellian Particle Velocity Distribution Functions for Spherically-Symmetric Solar-Windlike Plasma Systems and Consequences. II. The Case of Large Thermal Anisotropy and Nine Moment Description for Each Species, *Astrophys. J.*, **314**, 404–414, 1987.

Dryer, M., T.R. Detman, S.T. Wu, and S.M. Han, Three-Dimensional, Time-Dependent, MHD Simulations of Interplanetary Plasmoids, *Adv. Space Res.*, in press, 1989.

Dryer, M., and Z. K. Smith, MHD Simulation of Multiple Interplanetary Disturbances During STIP Interval VII (August 1979), in *Solar Maximum Analysis*, (V. E. Stepanov and V. N. Obridko, Eds.), Proceedings of the SMA/SMY Workshop, Irkutsk, USSR, June 17–22, 1985, VNU Science Press, Utrecht, 369–380, 1986.

Dryer, M., Z. K. Smith, T. R. Detman, and T. Yeh, MHD Simulation of the Interplanetary Environment in the Ecliptic Plane During the 3–9 February 1986 Solar and Geomagnetic Activity, Air Force Geophysics Laboratory Report AFGL–TR–86–0189, September 1986. ADA173822

Dryer, M., Z. K. Smith, and S. T. Wu, The Role of Magnetohydrodynamics in Heliospheric Space Plasma Physics Research, *Astrophys. Space Sci.*, **144**, 407–425, 1988.

Dryer, M., Z. K. Smith, S. T. Wu, S. M. Han, and T. Yeh, MHD Simulation of the "Geo-effectiveness" of Interplanetary Disturbances, in *Solar Wind-Magnetosphere Coupling* (Y. Kamide and J. A. Slavin, Eds.), AGU Chapman Conference, Terra Scientific Publishing Co., Tokyo, 191–197, 1986.

Garcia, H. A., and M. Dryer, The Solar Flares of February 1986 and the Ensuing Intense Geomagnetic Storm, *Solar Phys.*, **109**, 119–137, 1987.

Han, S. M., S. T. Wu, and M. Dryer, A Three-Dimensional,Time-Dependent Numerical Modeling of Supersonic, Super-Alfvenic MHD Flow, *Computers and Fluids*, **16**, 81–103, 1988.

Han, S. M., S. T. Wu, and M. Dryer, A Transient, Three-Dimensional MHD Model for Numerical Simulation of Interplanetary Disturbances, in *STIP Symposium on Retrospective Analyses*, 10–12 June 1985, Les Diablerets, Switzerland (M. A. Shea and D. F. Smart, Eds.), Book Crafters Publishing Co., in press, 1989a.

Han, S. M., S. T. Wu, and M. Dryer, A Numerical Study of Transient Thermally Conductive Solar Wind, in *Proceedings of STIP Symposium on Physical Interpretations of Solar/Interplanetary and Cometary Intervals* (M. A. Shea and D. F. Smart, Eds.), Huntsville, AL, 12–15 May 1987, Book Crafters Publishing Co., Chelsea, MI, in press, 1989b.

Panitchob, S., S. T. Wu, and M. Dryer, An Adaptive Grid Finite Difference Method for Transient MHD Flows, in *Developments in Mechanics, Volume 13*, Proceedings of the 19th Midwestern Mechanics Conference (C. H. Popelar, Ed.), Columbus, Ohio, 9–11 September 1985, pp. 236–237, 1986.

Pinter, S., and M. Dryer, Conversion of Piston-Driven Shocks from Powerful Solar Flares to Blast Waves in the Solar Wind, *Solar Phys.*, submitted, 1985.

Smart, D. F., M. A. Shea, M. Dryer, A. Quintana, L. C. Gentile, and A. A. Bathhurst, Estimating the Arrival Time of Solar Flare-Initiated Shocks by Considering Them to be Blast Waves Riding Over the Solar Wind, in *Proceedings of the Space Environment Forecasting Symposium*, Meudon, France (P. Simon, G. R. Heckman, and M. A. Shea, Eds.), U. S. Government Printing Office, Washington, D. C., pp. 471–481, 1987.

Smith, Z., T. Yeh, M. Dryer, T. Watanabe, H. Hirosawa, Z. Yamamoto, and K. Oyama, Comparison of MHD Simulation with Interplanetary Observations by the Spacecraft SAKIGAKE for the February 1986 Events, in *Proceedings of STIP Symposium on Physical Interpretations of Solar/Interplanetary and Cometary Intervals* (M. A. Shea and D. F. Smart, Eds.), Huntsville, AL, 12–15 May 1987, Book Crafters Publishing Co., Chelsea, MI, in press, 1989.

Song, M. T., S. T. Wu, and M. Dryer, A Linear MHD Instability Analysis of Solar Mass Ejections with Gravitation, *Solar Phys.*, **108**, 347–382, 1987.

Song, M. T., S. T. Wu, and M. Dryer, Soliton and Strong Langmuir Turbulence in Solar Flare Processes, *Astrophys. Space Sci.*, **152**, 287–311, 1989.

Tappin, S. J., M. Dryer, S. M. Han, and S. T. Wu, Expected IPS Variations Due to a Disturbance Described by a 3-D MHD Model, *Planet Space Sci.*, **36**, 1155, 1988.

Tappin, S. J., M. Dryer, S. M. Han, and S. T. Wu, A Simulation of the IPS Variations from a Magnetohydrodynamical Simulation, in *Proceedings of STIP Symposium on Physical Interpretations of Solar/Interplanetary and Cometary Intervals* (M. A. Shea and D. F. Smart, Eds.), Huntsville, AL, 12–15 May 1987, Book Crafters Publishing Co., Chelsea, MI, in press, 1989.

Wu, S. T., M. Dryer, and S. M. Han, Three-Dimensional, Time-Dependent MHD Simulation of Traveling Interplanetary Phenomena with Solar Origin, Extended Abstract, presented at the *Third International School of Space Simulations* (ISSS–3), Beaulieu, France, 22–27 June 1987, pp. 235–238, 1987.

Wu, S. T., M. Dryer, and S. M. Han, Recent Developments on the Numerical Simulation of Astrogeophysical Flows, in *Proceedings of the International Conference on Computational Engineering Sciences*, (ICE8–88), Atlanta, GA, 10–14 April 1988 (S. N. Atturi and G. Yagawa, Eds.), Springer-Verlag, Berlin, pp. 52 xi.1–52xi.2, 1988.

Wu, S. T., M. Dryer, R. S. Steinolfson, and E. Tandberg-Hanssen, The Effect of The Solenoidal Condition on the Numerical Magnetohydrodynamic Simulation of Coronal Dynamics, *Astrophys. J.*, **333**, 386–394, 1988.

Yeh, T., Polarity Neutral Lines on the Solar Surface and Magnetic Structures in the Corona, *Solar Phys.*, **107**, 247–262, 1987.

Yeh, T., Dynamics of Magnetic Flux Ropes in the Solar Atmosphere, in *Proceedings of STIP Symposium on Retrospective Intervals* (M. A. Shea and D. F. Smart, Eds.), Book Crafters Publishing Co., Chelsea, MI, in press, 1989.

FIGURE TITLES

Figure 1. A montage of some of our MHD modeling studies that illustrates our strategy for coupling studies for the photosphere, corona, and interplanetary domains. *Upper left panel*: a model for the extrapolation of photospherically measured vector magnetic fields; *lower left panel*: a filament eruption and CME-initiation model due to loss of equilibrium; *upper right panel*: coronal dynamic response to mass injection at the coronal base; *lower right panel*: several observed and interplanetary responses as modeled by our 2 1/2-D and 3-D MHD interplanetary global models (IGMs).

Figure 2. Solutions of two-fluid model equations with coupled electron-proton thermal conductivities for a quiet solar wind state characterized by the value $K = 482$ that corresponds to $nv = 2.8275 \times 10^8$ cm^{-2} s^{-1} (*dashed curves*). The various curves represent the various energies in normalized units as a function of the normalized distance $\lambda \equiv GM_{\odot}/\epsilon_t$ r; namely $E_k \equiv \psi/2$—the streaming energy; $E_{t,e} \equiv \tau_e$ —the electron thermal energy; $E_{t,p} \equiv \tau_p$ —the proton thermal energy; $E_{c,e} \equiv \theta_e$ —the electron conduction energy; $E_{c,p} \equiv \theta_p$ —the proton conduction energy; and $E_g \equiv -\lambda$—the gravitational energy. The solid curves represent the solutions corresponding to standard (Sturrock and Hartle (1966)-type equations (with uncoupled thermal conductivities). The arrows indicate the direction of the modifications in the standard solutions due to coupled thermal conductivities. (From Cuperman, Detman, and Dryer, 1988.)

Figure 3. Comparison of 2 1/2-D IGM simulation of multi-solar-flare and eruptive-prominence disturbances in August 1979 (near minimum of Solar Cycle 21) with ISEE–3 observations. The lower panels (left: velocity; right: IMF magnitude) show a simulation only of the hypothetical co-rotating streams; i.e., no simulated flares. The middle panels incorporate the superposition of the various flares (...their results at 1 AU indicated by arrows) and the corotating streams. The upper panels show the hourly averaged ISEE–3 observations.

Figure 4. Equatorial plane IMF lines and a plasmoid field line 72 hours after the initially spherical plasmoid is injected into the solar wind with a velocity twice that of the background value. Note the path of the fourth IMF line from left. Note that this line has managed to shift from the west side to the east side of the plasmoid. Reconnection plays a role in shifting this line from one side to the other. Some lines are able to simply slip around the plasmoid. These effects reduce the amount of field line draping, which is nevertheless quite apparent on the westward, anti-Sunward side of the plasmoid. (Based on code described by Han, Wu, and Dryer, 1988).

Figure 5. 'Snapshots' of the simulated solar wind velocity in the half-ecliptic plane during the solar/interplanetary events of February 1986, at the minimum of Solar Cycle 21. The 'flat' appearance represents the assumed uniform solar wind that varies between 250 km s^{-1} at 18 $R_{\odot}$ to 355 km s^{-1} at 1 AU. The observer 'looks' toward the Sun with the east limb (west limb) to the left (right). The snapshots on the simulation clock at t = 5.2, 15.2, 25.1, and 45.1 h correspond to the following times: 4 February, 04:12 UT; 4 February, 14:12 UT; 5 February, 00:06 UT; and 5 February, 20:06 UT, respectively. The vertical 'cliff' helps to indicate an occasional graphical scale change and, otherwise, should be ignored. In each panel, the undisturbed solar wind velocity in the foreground (1.1 AU) is equal to $\approx$ 355 km s^{-1}. (From Garcia and Dryer, 1987.)

Figure 6. *Lower Panel:* Schematic locations of the major solar flares, with respect to the Sun-Earth axis, and a representative location of SAKIGAKE (0.84 AU, 57°W of Earth) during the period 3–7 February 1986. The arcs drawn on each arrow represent the 18° azimuthal width of sinusoidal shock input pulse for each flare.

Middle Panel: Simulated contours of $\mathrm{Log}_{10}(nV_R)$ at 0806 UT on 6 February 1986. The locations of Earth, SAKIGAKE, and the line of sight are also shown.

Upper Panel: Comparison of the MHD simulation (curve, scale on left) and the IPDS data (vertical bars, scale on right) from SAKIGAKE at 0.84 AU, 57°W of Earth. (From Garcia and Dryer, 1987; and Smith et al., 1989.)

Figure 7. Interplanetary imagery: the left side of the figure shows an IPS map from Cambridge University's radio telescope (operating at 81.4 MHz) on 19 September 1980 as part of a synoptic observational period in 1979–1980. The color coding refers to the ratio, g, of the scintillation index in the weak scattering region (outside of elongations > ~ 35° at this frequency, where the r.m.s. phase variations are less than 1 radian) divided by the scintillation index averaged over a 1-year period within each pixel (5° × 5°) for more than 2000 radio sources. The outer ellipse denotes the zone covered during the meridian transit at Cambridge as these radio sources are detected from the anti-solar position and as the telescope rotates from right to left, past the Sun (center of ellipse), and back again to the anti-solar position during the UT day. Ratios of $g > 1$ indicate compression; $g < 1$, rarefaction. In the present case, a flare and disappearing filament event took place at about N24°E15° on 17 September 1980 and produced the interplanetary disturbance (as modeled by a 3-D MHD model on the right side of the figure) that propagated Earthward and generated the sudden commencement of a geomagnetic storm. (Based on results in Tappin, Dryer, Han, and Wy, 1988, 1989.)

Figure 8. Average trajectory characteristics (based on a sample of 39 cases along a helioradial line coincident with the flare normal) of flare-generated interplanetary shock waves. The average piston-driven shock velocity is 1560 km s^{-1} for large flares. This shock is driven to an average distance of 0.12 AU where it begins its deceleration as a classical blast wave convected by the ambient solar wind. The average velocity from the point of conversion to a blast shock to its arrival at 1 AU is 590 km s^{-1} and, added vectorially to a representative solar wind velocity of 300 km s^{-1}, provides a shock velocity in the inertial frame of 890 km s^{-1}. (Pinter and Dryer, 1985.)

PHOTOSPHERE/CORONAL/INTERPLANETARY COUPLING STUDIES

GOAL: TO UNDERSTAND THE FUNDAMENTAL PHYSICS OF ENERGY AND MOMENTUM TRANSPORT FROM SOLAR SURFACE THROUGH THE CORONA TO INTERPLANETARY SPACE VIA NUMERICAL SIMULATION

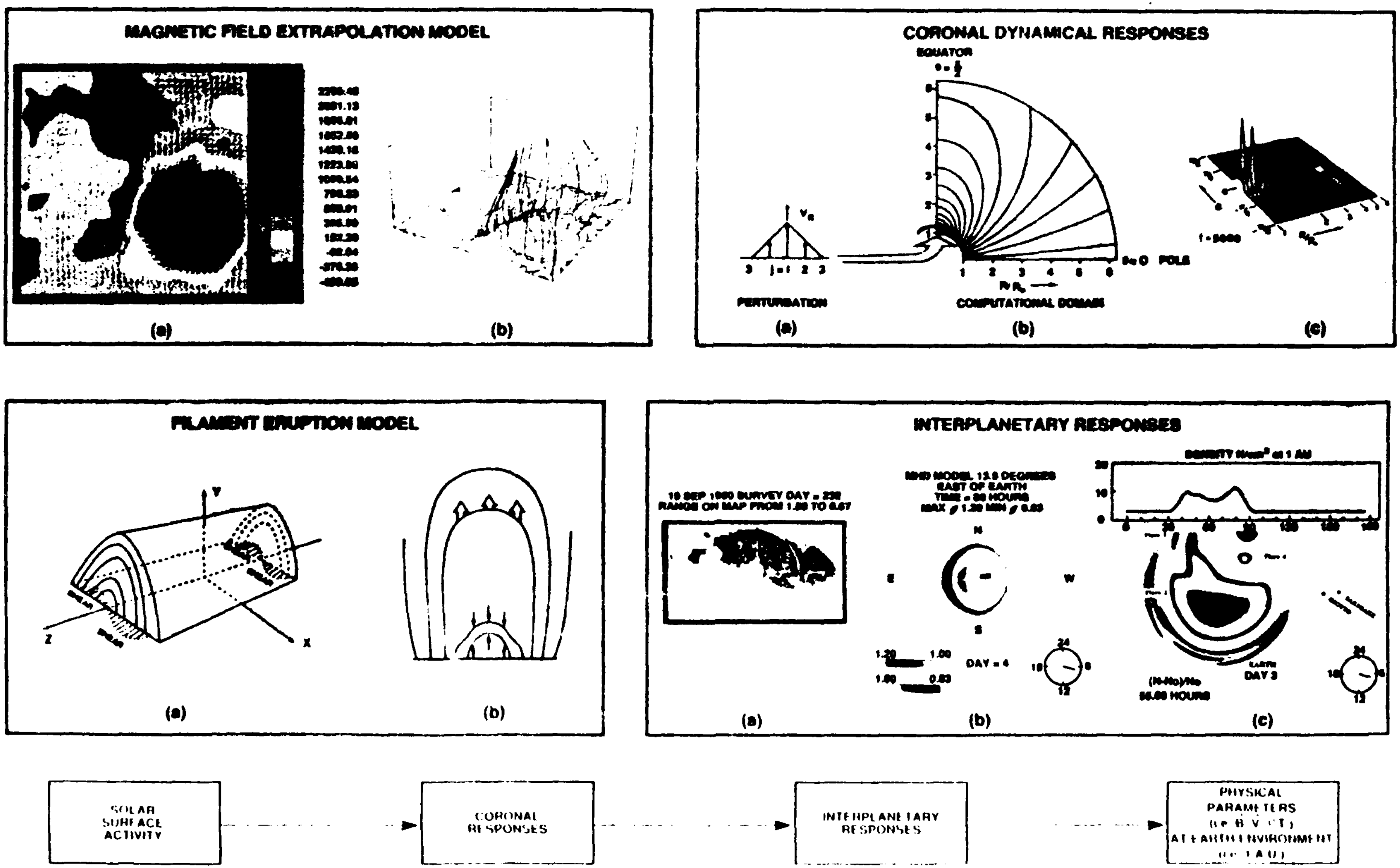


FIGURE 1

TWO-FLUID SOLUTIONS FOR QUIET SOLAR WIND

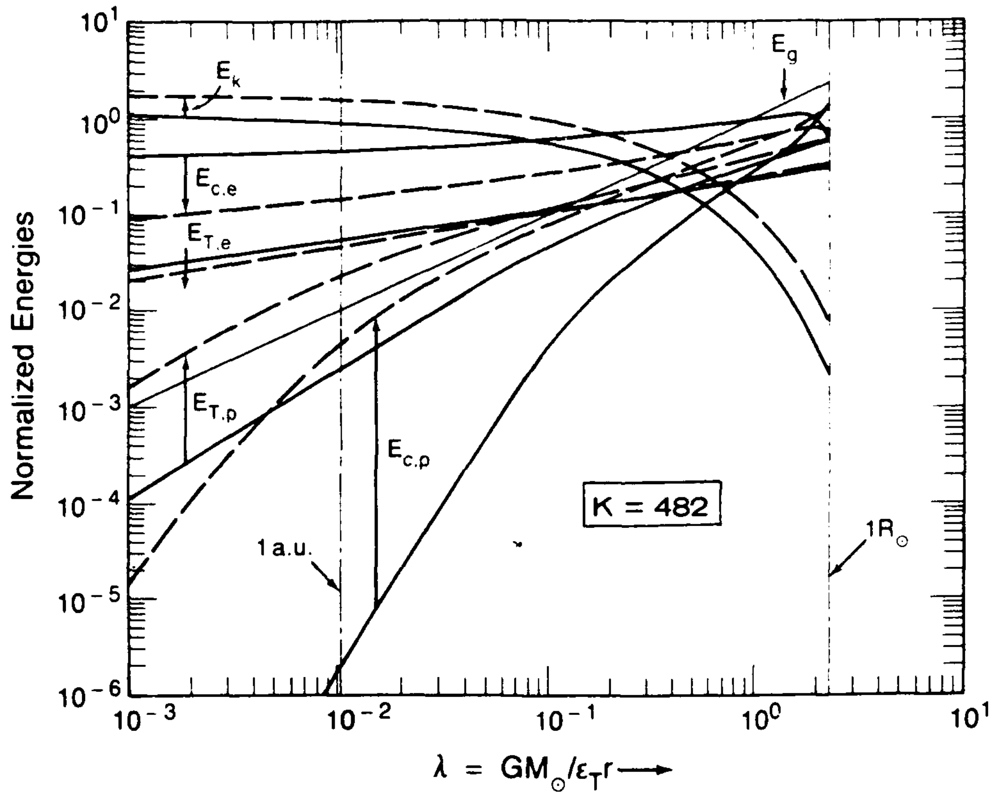
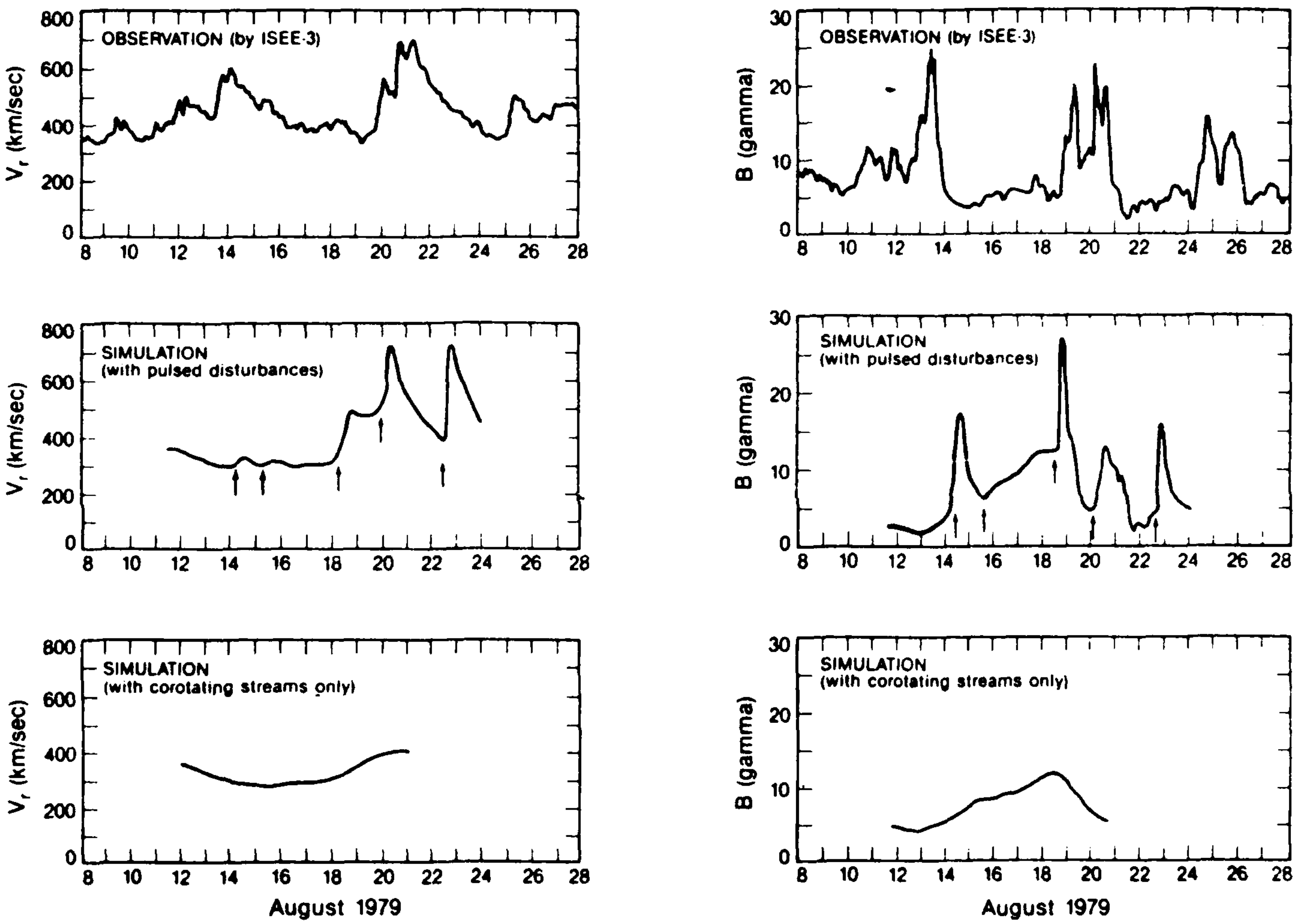


FIGURE 2



OBSERVATION (by ISEE-3)
SIMULATION (with pulsed disturbances)
SIMULATION (with corotating streams only)
V_r (km/sec)
B (gamma)
August 1979

FIGURE 3

MAGNETIC FIELD LINES

HILL MAGNETIC BUBBLE, VB2B, VCL=2, COS

time 72.64 hours

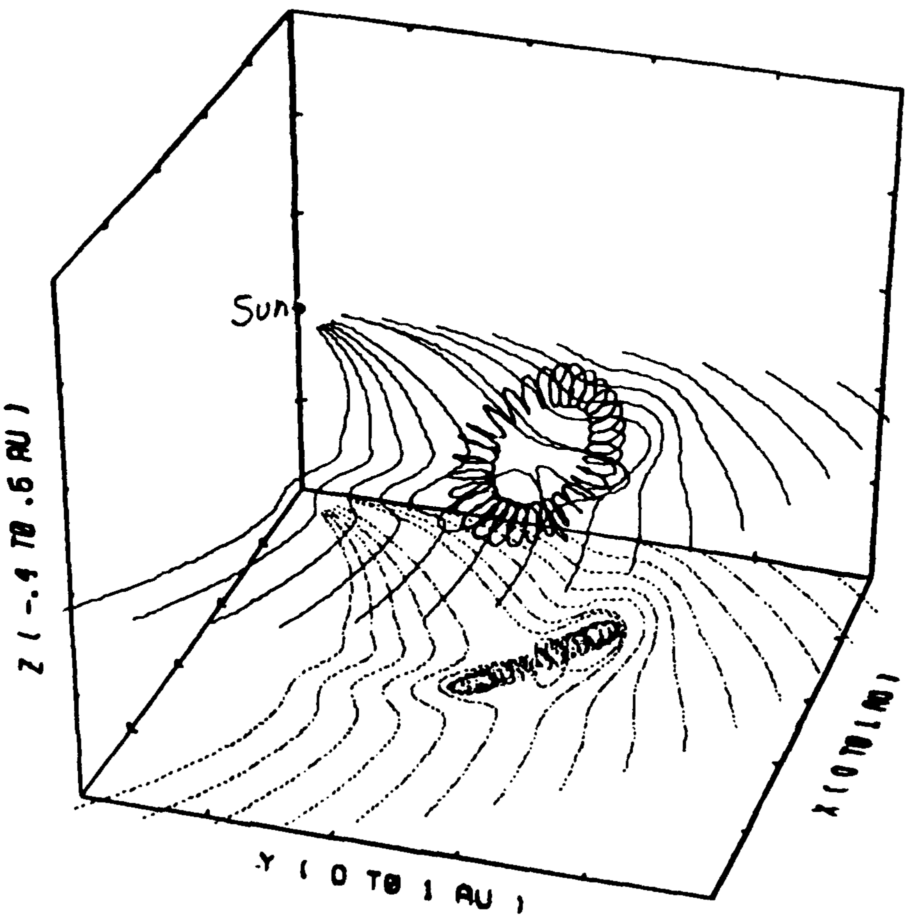


FIGURE 4

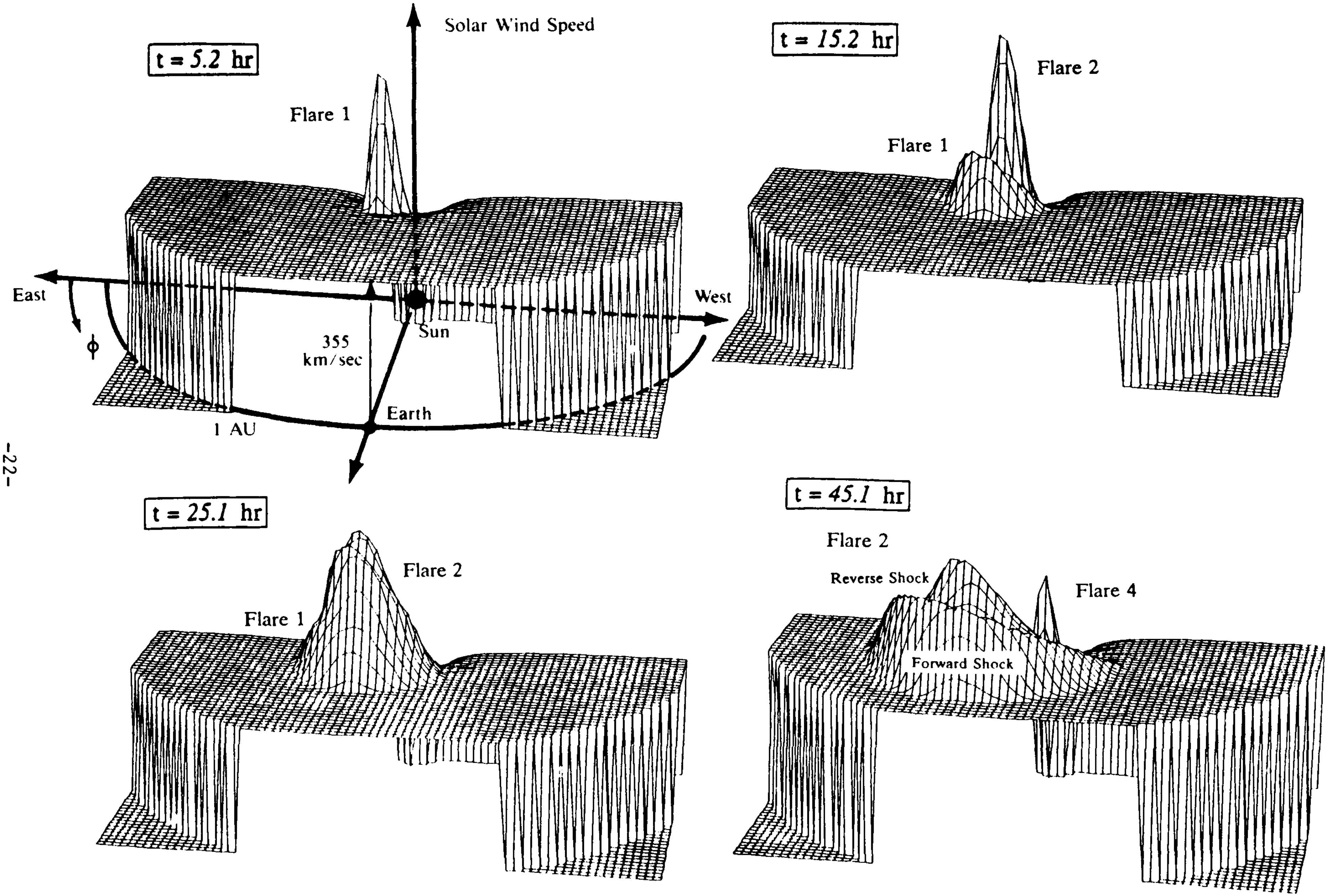
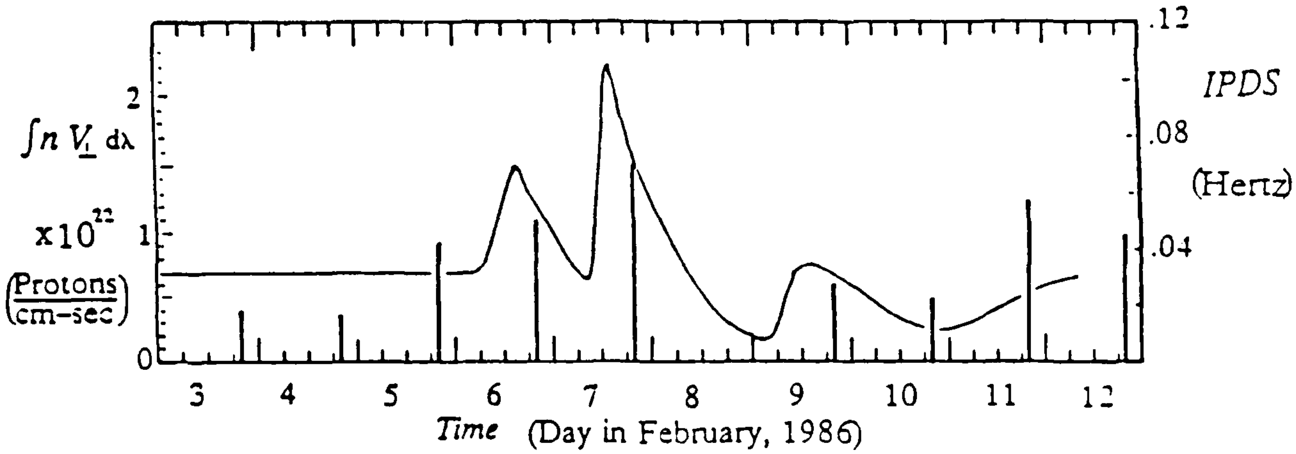
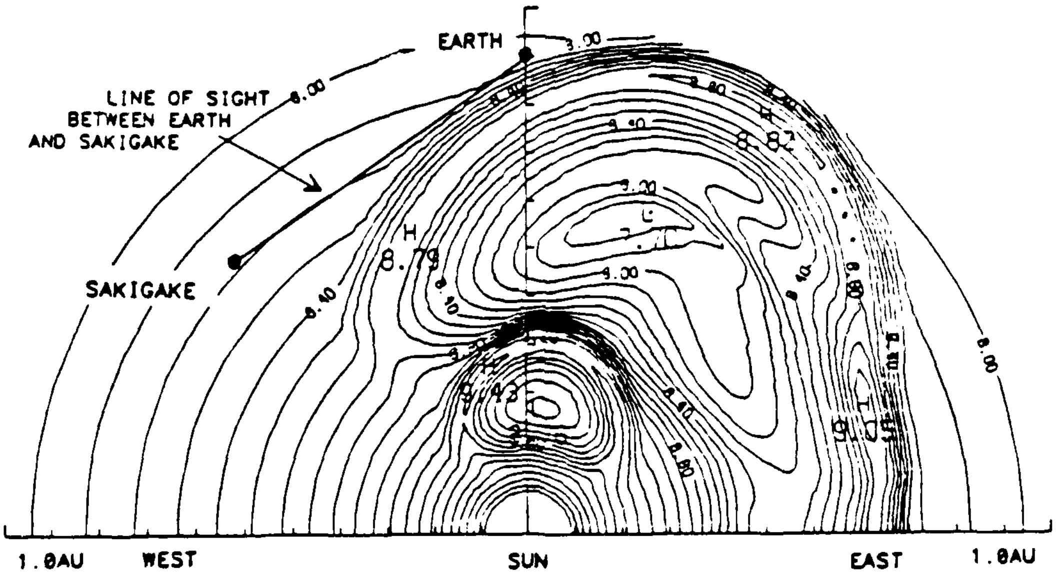

t = 5.2 hr
Solar Wind Speed
Flare 1
East
West
Sun
355
km/sec
Earth
1 AU
t = 15.2 hr
Flare 2
Flare 1
t = 25.1 hr
Flare 1
Flare 2
t = 45.1 hr
Flare 2
Reverse Shock
Forward Shock
Flare 4

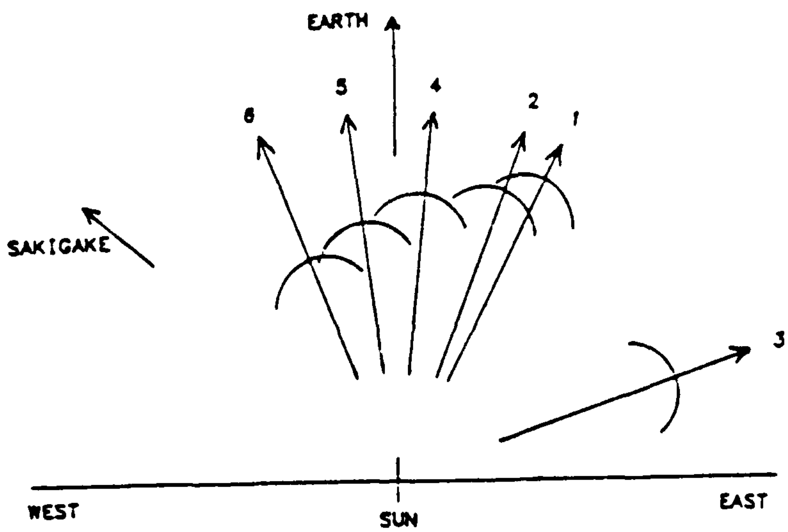
FIGURE 5



IPDS
(Hertz)
Time (Day in February, 1986)



EARTH
LINE OF SIGHT
BETWEEN EARTH
AND SAKIGAKE
SAKIGAKE
1.0AU
WEST
SUN
EAST
1.0AU



EARTH
SAKIGAKE
WEST
SUN
EAST

FIGURE 6

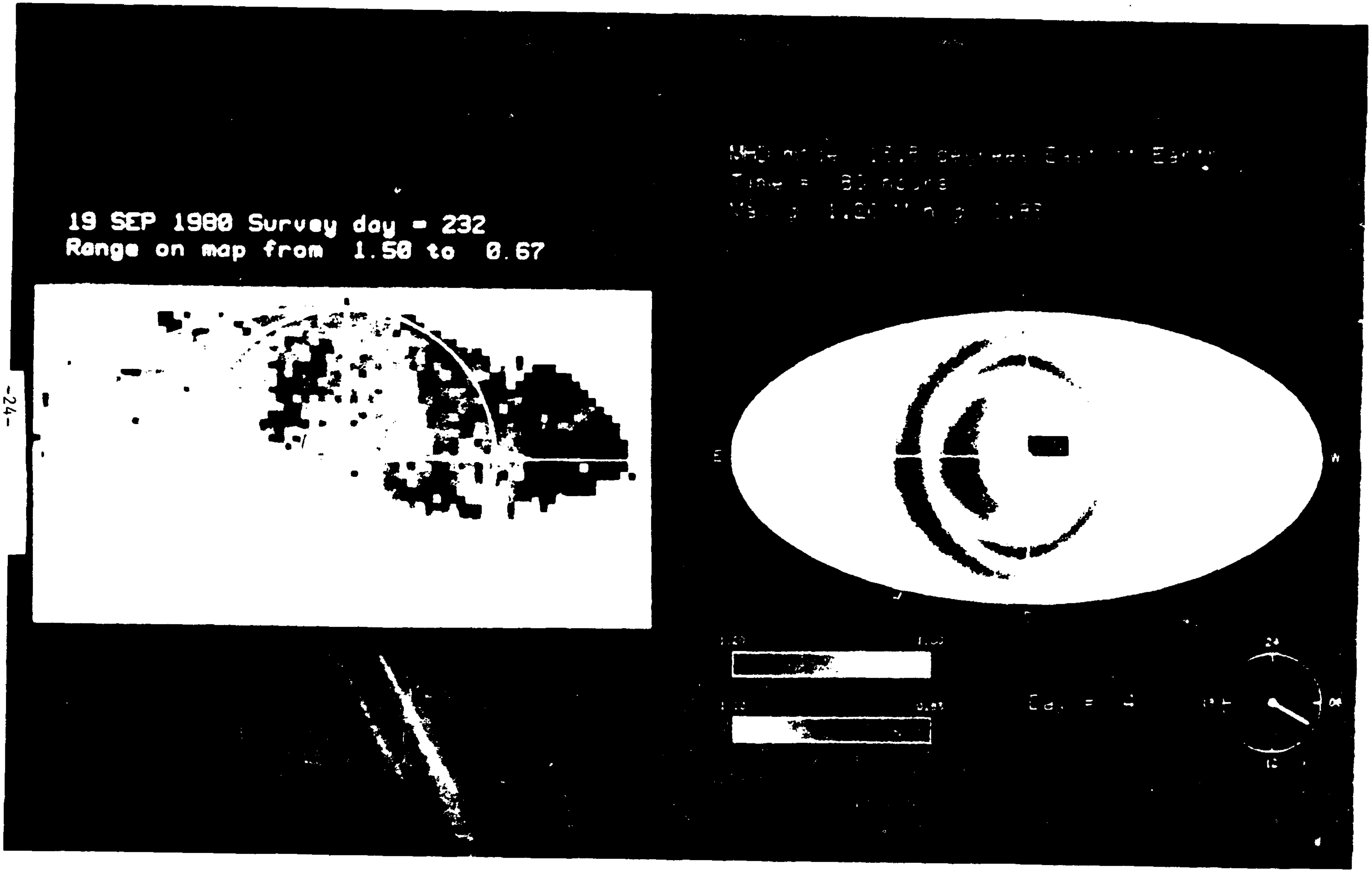


FIGURE 7

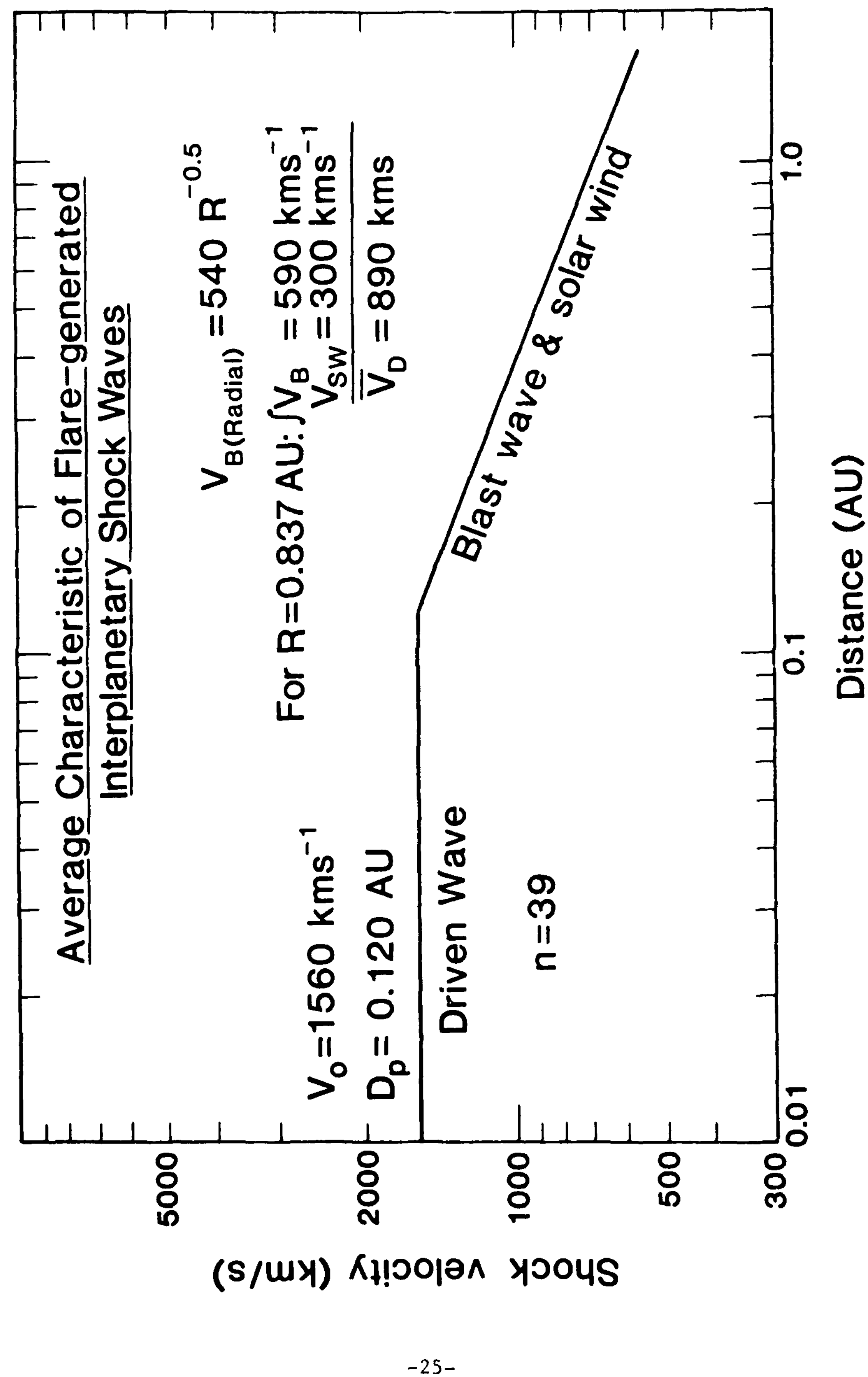

Average Characteristic of Flare-generated
Interplanetary Shock Waves
$V_{B(Radial)} = 540\ R^{-0.5}$
For R=0.837 AU: $\int V_B = 590\ kms^{-1}$
$V_{SW} = 300\ kms^{-1}$
$\overline{V_D} = 890\ kms$
$V_o = 1560\ kms^{-1}$
$D_p = 0.120$ AU
Driven Wave
n=39
Blast wave & solar wind
Shock velocity (km/s)
5000
2000
1000
500
300
0.01
0.1
1.0
Distance (AU)

FIGURE 8.